View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 44 (2016) 389 – 394

www.elsevier.com/locate/procedia

6th CIRP Conference on Assembly Technologies and Systems (CATS)

Robot Station Optimization for Minimizing Dress Pack Problems

Johan S. Carlson[a], Jonas Kressin[a,*], Tomas Hermansson[a], Robert Bohlin[a], Mathias Sundbäck[b], Henri Hansson[b]

[a]*Fraunhofer-Chalmers Centre, Chalmers Science Park, SE-412 88 Gothenburg, Sweden*
[b]*Volvo Car Corporation, SE-405 31 Gothenburg, Sweden*

* Corresponding author. Tel.: +46031-7724274; fax: +46031-7724260. *E-mail address:* jonas.kressin@fcc.chalmers.se

Abstract

Problems with robot dress packs are one of the major reasons for online adjustments of robot motions and for down time in robot stations. A factory study showed that many robots wear out more than one dress pack per year. The life length variation was in fact shown considerable, ranging from years to only months. The dress packs consist of attached cables and hoses which typically have significant impact on allowed robot configurations and motions in the station.

In this paper, we present novel simulation methods for improving robot configurations and motions during off-line programming and optimization of robot stations. The proposed method is applied to a stud welding station resulting in the elimination of several problems related to the dress packs.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the 6th CIRP Conference on Assembly Technologies and Systems (CATS)

Keywords: automation; simulation; motion planning; optimization; robotics and dress packs

1. Introduction

In a highly automated production factory for complex assembled products there could be up to several hundreds of robots organized into lines and stations for handling and joining operations. Therefore, the factory is a huge investment and return on investment requires high product quality, factory throughput, equipment utilization, and flexibility as well as low energy consumption [1,2].

Many industrial robots are externally dressed with cables and hoses feeding the tool with signals, power, air, screws, paint and sealing material etc. These dress packs have serious impact on the allowed robot configurations and motions in a robot station. The reason is the risk of early breakage due to high stresses and wear. For example, a robot hose in a body shop cycles through the same motion every, say, minute. The hoses are often affected by large deformations, sometimes contacts with the robot links and in worst case with the surrounding geometries. This type of breakdown of robot cables is a big concern in the factory creating replacement cost and down time. A factory study at Volvo Cars showed that 47% of the robots wear out more than one dress package per year [3]. The life length variation was shown considerable, ranging from months to years. Out of all dress pack related breakdowns, 61% were considered to be major, i.e. takes more than 30 minutes to resolve [4]. The study also showed an existing potential to improve the situation with an estimation of 14% wear out instead of 47%, if appropriate actions were to be taken. Besides this, the robotic cable protection company REIKU claims that ”Almost 85% of Robotics and Automation ”downtime” can be directly attributed to cable or hose failure” [5]. Also [6,7] report that failing cables are the foremost cause of downtime for industrial robots. Robot programming experts, points at the root cause likely was the lack of proper optimization of the robot path [3]. Therefore, if the dress pack wear would be considered at an early stage of planning, then it would have a significant effect on the breakdowns.

Considering that for example a vehicle Body-in-White process involves hundreds of robots [2] shows the potential of improvements in the life length of robot cables. Today, the

2212-8271 © 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the 6th CIRP Conference on Assembly Technologies and Systems (CATS)
doi:10.1016/j.procir.2016.01.022

robot manufacturers provide rules of thumbs on how to avoid high stresses, and collisions are removed by experience and on-line adjustments. However, recent progress in real time simulation of cables [8] makes it possible to determine how robot cables are deformed during the robot motions. This together with technology for automatic path planning and line balancing [2] will in this paper be used to develop novel strategies for finding feasible robot configurations and improved motions with respect to equipment utilization/cycle time and life length of cables.

Despite the importance and potential, there exist only a few published methods on how to include a physical correct dress pack in off-line programming of robot stations [9,10] .

The paper has the following outline: In Section 2, the mechanical and mathematical model for real time simulation of dress packs is introduced. Then, in Section 3, an xml scheme for modeling and storing dress packs in a reusable way is defined. In Section 4, a scan2flex method for determining effective material properties of complex dress packs is described. Section 5 shows the state of the art of automatic optimizing of robot stations and the problems caused by not including the dress packs. Seeing that, Section 6 shows how and the improvement of including the dress packs in the planning. Finally, Section 7 concludes the paper and discusses future possible research.

2. Dress pack simulation model

The robot dress pack consists of multiple flexible objects such as electric cables and supply hoses tied to each other in a complex way. In order to compute the elastic deformation of the dress pack when subject to a robot motion, we need a proper simulation model. The model must be physically accurate and able to predict large nonlinear deformations. It must also support a variety of boundary conditions to connect the flexible objects to each other as well as to the robot.

2.1. Cosserat rod theory

A *rod* is characterized as a slender object in R^3 , where one dimension (the length) is significantly larger than the other two (the cross section) and that exhibits an elastic behavior. Assuming the cross section is planar and rigid, the configuration q of a flexible segment of length L can be represented by an arc length parameterized framed curve:

$$q: [0, L] \ni s \to \big(\varphi(s), R(s)\big) \in \mathrm{SE}(3). \quad (1)$$

Here, $R(s) = (d_1, d_2, d_3) \in \mathrm{SO}(3)$ describes the evolution of the cross section orientation along the center curve φ.

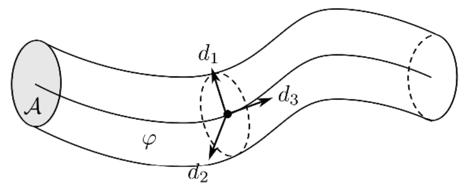

Fig. 1. A rod representation of a cable.

Geometrically exact *Cosserat rod theory* accounts for elastic deformations in the form of both shearing, stretching, bending and torsion. The total potential energy of a configuration q is written

$$W = \int_{s=0}^{L} \{\Gamma(s)^T K_\Gamma \Gamma(s) + \Omega(s)^T K_\Omega \Omega(s) - K_g g^T \varphi(s) + w_C(s)\} ds \,. \quad (2)$$

Γ is the shearing/stretching strain vector and Ω is the curvature/torsion strain vector in the material coordinate system R. K_Γ and K_Ω are the corresponding effective stiffness matrices. Furthermore, K_g is the length density and w_C is a repelling potential energy density due to conservative contact forces.

According to the Hamiltonian principle, the static mechanical equilibrium of the rod can be found among the stationary points to the total potential energy,

$$\delta W = 0. \quad (3)$$

2.2. Boundary conditions and clips

The energy formulation of our mechanical system extends naturally to the modelling of multiple flexible segments connected to each other. A wide range of boundary conditions and kinematic clips can therefore be represented by expressing the kinematic relation between connection points in terms of generalized coordinates. In addition to that, link weights and elastic joint springs can easily be modelled by adding corresponding energy terms to the total potential energy of the system.

2.3. Implementation notes

For an efficient implementation of a discrete Cosserat rod model, the potential energy densities are evaluated in terms of geometric finite differences and integrated along the rod with a suitable quadrature rule. Solving Eq. (3) with a quasi-Newton method together with analytically calculated gradient expressions allows for a real-time simulation of the entire dress pack.

3. Dress pack library

In order to efficiently be able to reuse a modelled dress pack on different simulation scenarios with different robot types, there is a need for building a library infrastructure for connecting a dress pack to a robot. Since various parameters of a dress pack can be adjusted and customized for each individual robot (e.g. mounting positions and dress pack lengths), the infrastructure should include the possibility to easily adapt such parameters when mounting a dress pack to a robot. It also needs to support various types of attachments that are found in industrial applications, including e.g. fixed (clamped) attachments, guiding supports and retracting units. Figure 2 shows examples of different types of attachments for robot dress packs.

In order to simulate the deformations of a dress pack subject to robot movements, including the different types of dress pack attachments, the software *Industrial Path Solutions (IPS)* is used. IPS is capable of real-time simulation of flexible materials (for example cables and hoses) as well as off-line robot programming using automatic algorithms.

To ensure an efficient work flow for using the dress pack library, it needs to cover the complete work process of storing, accessing and attaching different dress packs to different robots. To store the information of flexible segments and how they are interconnected, the *Harness Model Description (HMD)* format can be used. *HMD* is an XML-based format that describes the shape, dimensions and material properties of flexible segments, as well as how flexible segments are connected to each other and to coordinate frames in space, referred to as *Nodes*. The format is also capable of describing more complex attachment types, like kinematic parts such as the retractor in Figure 2(c). The location in space for a kinematic attachment, consisting of rotating and/or translating joints and link geometries, is also defined by a *Node*. Due to its completeness in describing the different components of a robot dress pack, *HMD* is suitable for building a dress pack library. The *HMD* format is fully compatible and integrated with the IPS software.

With a library infrastructure in place, the final part to specify is an *attachment interface* describing how different parts of the dress pack should connect to different parts of the robot. An industrial robot typically consists of six revolute joints, each one having a link geometry associated. Link zero (the base) is static, link one is attached to joint one, link two to joint two etc. By defining the attachment interface as a set of transformations, each one associated with a particular robot link and a particular Node in the *HMD* structure, the attachment of the dress pack can be fully described. An attachment, A_i, between a certain robot link and a certain Node can then be described as

$$A_i = \{T_i, ID_L, ID_N\} \quad (4)$$

where T_i is the local transformation from the link coordinate system, ID_L is an id number for the robot link and ID_N is a unique id number for the Node.

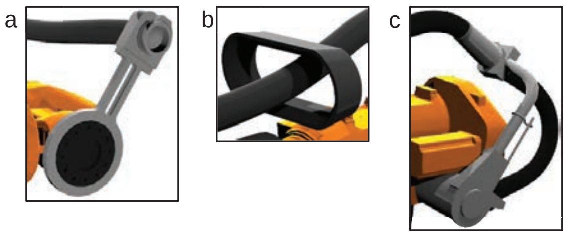

Fig. 2. (a) Robot link six attachment; (b) Link three guiding frame; (c) Link three retractor that pulls the dress pack to limit its occupying space.

4. Scan2Flex

In order for a simulation model to predict correct deformations, it is crucial that the material parameters K_Γ, K_Ω and K_g of the rod model are authentic. In many cases, such as for the stud robot dress pack, it is difficult to setup classical force-displacement measurements, e.g. 3-point bending. An alternative method is *Scan2Flex*, a parameter estimation method based on geometric matching described in [12]. The stud robot is then placed in different distinctive poses and the dress pack is scanned into a 3D point cloud format. The unknown material properties of the simulation model are then identified by seeking the ones that provide the best geometric match between the model and the set of scanned reference shapes. The outcome of the method depends on how well the set of reference shapes encode the different strain types and the choice of a geometric matching metric between space curves.

For the stud robot dress pack, the nominal length (L = 1.27 m) and mass (m = 1.4 kg) were explicitly known and hence the length density K_g could be determined. The non-zero stiffness parameters were then estimated to:

$$K_{\Gamma,33} = 111\ N$$
$$K_{\Omega,11} = 0.684\ Nm^2$$
$$K_{\Omega,22} = 0.684\ Nm^2$$
$$K_{\Omega,33} = 6.32\ Nm^2$$

Figure 3 shows three of the scans that were used to acquire the material parameters, together with simulated dress packs. In total seven different scans were used with varying twist of the end grip.

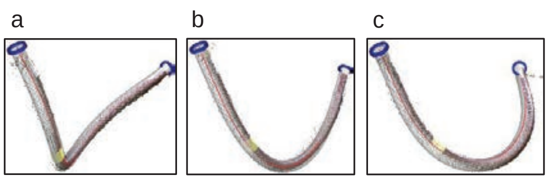

Fig. 3. Three of the scans used to acquire material parameters, together with simulated dress pack. (a) End grip twisted -90°; (b) No twist; (c) End grip twisted +90°.

5. Robot station optimization

Fig. 4. Stud welding station (Courtesy of Volvo Cars).

To program robot motions and find a time efficient sequence for the robots in a station like the stud welding station shown in Figure 4 is a time consuming and challenging task. The programming can be done by using the real physical robot or by using a computer model of the robot. The latter is a digitalized version of teach in programming and is called off-line programming (OLP). OLP has many advantages such as better equipment utilization and faster introduction of new product models. However, one of the main advantages is that by using OLP one can further reduce the programming time and improve the program by math-based algorithms for motion planning and combinatorial optimization. The overall approach for optimization of travel time in robot station consists of four major elements, (i) task planning to find promising configurations that can reach each weld collision freely, (ii) balancing welds between the robots, (iii) sequence optimization and motion planning to select one solution for each weld and connect them together by efficient motions and in a sequence minimizing traveling time, and (iv) coordination of the robots to avoid collision between the robots with a minimal increase of cycle time. For more details see [1,2,11]. The factory stud weld station consisting of 4 robots performing 46 welds on the floor of the car body. By applying the above methodology for optimization of the cycle time we can reach a cycle time of 34.0 sec (assuming 2 sec per weld including stop time and kinematic movements of tool). Next, the optimized solution will be analyzed with regard to its impact on the dress packs.

5.1. Analysis of the Dress Packs

The dress packs are added to the robots in the virtual version of the stud station. Then, by running the motions the behavior of the dress packs can be observed and the following serious issues identified; (i) Collision during weld operation, to surrounding or other robot (Figure 5.(a)), (ii) Twisting of dress pack around robot arm (Figure 5.(b)), and (iii) Collision during inter path, to surrounding or other robot (Figure 5.(c)). In the next section we look into methods for resolving issue (i), (ii) and partially issue (iii).

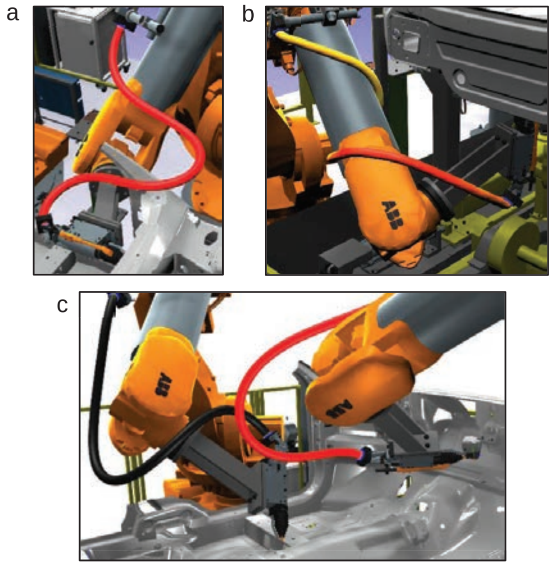

Fig. 5. (a) Dress pack colliding with car body during weld operation; (b) Dress pack twisted around robot arm; (c) Dress pack colliding with other robot during inter path.

6. Joint restrictions and task planning for reducing dress pack problems

To fully address the problems with the dress packs from section 5.1, the dress packs could be simulated during the optimization and automatic path planning. However, as described in [10], since the shape of the dress pack is not deterministically established by a given robot configuration, it is challenging to consider the dress packs in an optimization algorithm. Therefore we suggest a novel simulation approach consisting of the following two methods:

- Joint restrictions
- Task planning with dress packs

6.1. Joint restrictions

A simple yet effective way of minimizing damage to a dress pack is to apply *joint restrictions* [10]. By prohibiting the robot from being at certain configurations in joint space, some types of dress pack damage can be limited or even completely avoided. In this way the dress pack is to some extent considered during the robot optimization without any actual simulation of the flexible dress pack.

When twisting of the dress pack occurs (the second problem identified in section 5.1), the tension force in the dress pack rapidly increases as the dress pack gets stretched. By analyzing the joint trajectory for the robot, and correlating with high tension force in the dress pack, a relationship can be established. For the stud welding station, the neutral tension force in a dress pack varies between 5 – 25 N during the robot motion. However when the dress pack gets twisted around the robot arm, the tension force peaks at 2776 N. This occurs when joints four and six are rotated in a certain combined way. By introducing a simple expression limiting the absolute value of the sum of joints four and six, the robot will be limited to enter areas in its configuration space with high probability of dress pack twisting. From investigation of the joint values in correlation with the high tension force, the limit in expression (5) is derived:

$$|j_4 + j_6| \leq 270°. \quad (5)$$

Since (5) is a simple logical condition, it is easily applied to the robot model. During the different steps of the optimization, described in Section 5, the joint limit condition will be considered with negligible computational effort. In this way twisting of the dress pack will be less likely to occur in the generated solutions.

6.2. Task planning with dress packs

One of the main issues identified in section 5.1 was collision between the dress pack and surroundings. To account for collisions when performing path planning, the shape of the dress pack needs to be known at the start and goal configuration of the path. Since the shape is dependent on previous travelling path of the robot, and since this path is continuously changing in the sequencing algorithm, it is not possible to determine the shape until the entire sequence has been established.

Instead we will focus on addressing the problem of collisions during weld operations. By identifying and removing task alternatives that produce bad measure values for the dress pack, only good candidates will be used in the load balancing, sequencing and path planning. To find out if a robot configuration γ_i is damaging for the dress pack, we introduce a cost $C(\gamma_i)$ for cable wear as suggested in [10]:

$$\begin{aligned} &C(\gamma_i) = C_\kappa(\gamma_i) + C_F(\gamma_i) + C_d(\gamma_i) \quad (6) \\ &C_\kappa(\gamma_i) = w_\kappa \cdot max(0, \kappa(\gamma_i) - \kappa_0)^2 \\ &C_F(\gamma_i) = w_F \cdot F(\gamma_i)^2 \\ &C_d(\gamma_i) = w_d \cdot min(0, d(\gamma_i) - c)^2. \end{aligned}$$

The parameters for the cost function (6) are given by Table 1 and

- $\kappa(\gamma_i)$ is the largest curvature of the dress pack,
- $F(\gamma_i)$ is the largest tension force,
- $d(\gamma_i)$ is the shortest distance to any static geometry.

Table 1. Parameters for cable wear cost function.

Parameter	Description
κ_0	Smallest curvature for the curvature penalty to take effect
w_κ	Cost weight, curvature
w_F	Cost weight, tension force
w_d	Cost weight, shortest distance
c	Threshold for clearance cost

The cost function in (6) takes into account a combined cable measure of curvature, tension force and clearance to collision. To compute a value for the cost function when the robot is at a certain task alternative, the shape of the dress pack needs to be determined. By creating a straight motion in joint space from the robot home position to the task alternative, a reasonable dress pack shape can be established and the cost function calculated. When all costs for a certain weld task have been calculated, for all robots and all alternatives, they are compared against each other. An alternative is kept if the following condition is satisfied:

$$C(\gamma_i) \leq T \ \vee \ C(\gamma_i) \leq \alpha \cdot C_{min}, \quad (7)$$

where T is a static threshold, C_{min} is the lowest cost for the task (among all alternatives between all robots) and α is a scaling constant to ensure not all alternatives for a weld task are removed. By removing all high-cost alternatives, the remaining alternatives form a better starting point for the load balancing and sequencing step.

6.3. Results from new optimization

To test the methods of joint limitation and task alternative elimination from Sections 6.1 and 6.2 they are applied on the virtual stud welding station from Section 5. A *task planning with dress packs* is executed with *joint restrictions* enabled for all robots, and a total number of 360 different task alternatives are found (compared to 790 alternatives in the original case). A load balancing and sequencing is performed on the remaining task alternatives, and a feasible solution is found with a cycle time of 36.4 sec (2.4 sec increase compared to the original optimization without considering the dress packs).

To visualize the impact on the dress packs from the new optimization, they are added to the robots and simulated during the new robot motions. As a first comparison, the weld tasks with dress pack issues in Figure 5.(a) and 5.(b) are analyzed. As can be seen in Figure 6.(a) and 6.(b) the issues for these tasks have effectively been eliminated in the new solution.

For further comparison of the entire robot program, the cable wear cost function is evaluated for each robot during its entire motion. The cost function is evaluated both in the original and in the new program, and compared. As an example, Figure 7 shows how the cost function varies during the entire motion for robot 3, both for the original and the new program. In the original program, the highest peak occurs when the robot moves away from the weld task in Figure 5.(a), as the robot pulls the dress pack which is stuck to the car body. As a measure of the overall contribution of the cost function, the

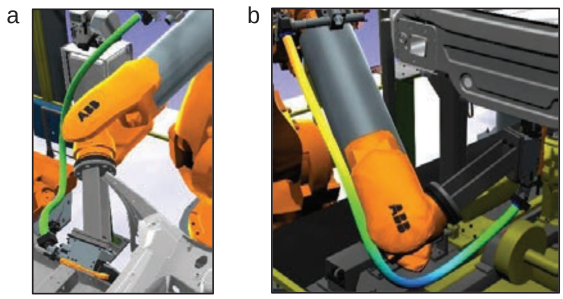

Fig. 6. (a) Dress pack collision-free during weld operation; (b) Dress pack without twist around robot arm.

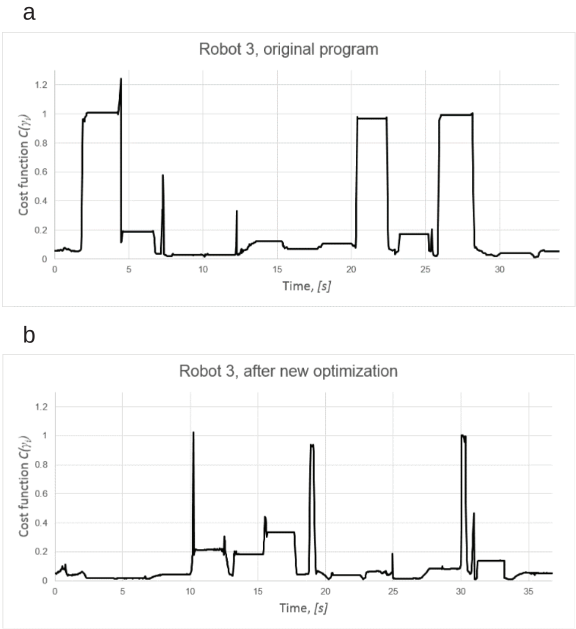

Fig. 7. (a) Cost function robot 3, original program. Integral cost = 9.2; (b) Cost function robot 3, after new optimization. Integral cost = 3.9.

numerical integral is used. Using the integral as a measure, as opposed to using the maximum value, reduces the contribution of potential outliers in the cost function. The integral cost is calculated to 9.2 for the original program and 3.9 for the new program.

As a final comparison, the integral of the cost function is computed for each robot, both for the original program and the new program. The results are presented in Table 2, together with the total cycle time for each case showing that the proposed method has significantly improved the dress pack related problems but increased the cycle time with 2.4 sec.

Table 2. Result comparison between original case and optimization with dress pack consideration. The high cost for robot 1 in the original case comes from the twisting problem illustrated in Figure 5.(b).

Case	Integral of cost function				Cycle time [s]
	R1	R2	R3	R4	
Original	1685	5.1	9.2	9.6	34.0
New optimization	5.1	3.1	3.9	2.2	36.4

7. Conclusions and future research

The analysis of the original program showed serious issues with the simulated dress pack, which in reality would make the program non-feasible for the robots to perform without seriously damaging the dress packs. Also, the results from section 6.3 show that with the suggested methods a lower integral of the cable wear cost function could be achieved for all robots in the stud welding station. What remains to be validated is how a value for the cost function based upon a simulated dress pack translates to a scenario with a real dress pack.

For future work we suggest investigating the inclusion of dress pack simulation in the context of load balancing, sequencing and path planning. By incorporating dress pack simulation, the optimization algorithms could produce cycle-time optimized, collision free robot programs with minimized damage to the dress packs. One of the main challenges is determining the shape of the dress pack before the final robot motion has been established. As suggested in [10], one way of dealing with such uncertainties is to classify robot configurations as robust or non-robust w.r.t. cables. A non-robust configuration involves an uncertain dress pack shape that is highly dependent on the robot's travelling path to reach the configuration. By eliminating such configurations, the shape of the dress pack would be easier to determine during the different steps of the optimization algorithms.

Acknowledgements

This work was carried out within the Wingquist Laboratory VINN Excellence Centre, supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA). It is also part of the Sustainable Production Initiative and the Production Area of Advance at Chalmers University of Technology.

References

[1] Björkenstam S, Spensieri D, Carlson J S, Bohlin R, Gleeson D. “Efficient Sequencing of Industrial Robots through Optimal Control”, Procedia CIRP 23, 194-199, 2014.
[2] Segeborn J, Segerdahl D, Ekstedt F, Carlson J S, Andersson M. ”Industrially Validated Method for Weld Load Balancing in Multi Station Sheet Metal Assembly Lines”, Journal of Manufacturing Science and Engineering 136 (1), 2014.
[3] Eriksson, U. Poor Life Length of Cable Packages. Volvo Cars, Göteborg, 2005.
[4] Eriksson, U. Excessive Exchange of Hose Packages. Volvo Cars, Göteborg. 2005.
[5] REIKU. Robotic cable management systems. http://www.reikuna.com/catalogue-library (accessed May 3rd 2013). File: REIKU Robotic Cable Management.pdf.
[6] Igus. The Less-is-More Approach to Robotic Cable Management. http://www.igus.com/wpck/default.aspx?Pagename=The_Less_is_More_Approach_to_Robotic_Cable_Management&C=US&L=en (accessed May 3rd 2013).
[7] Drives & Controls. Wireless sensors replace vulnerable robot wiring. http://www. drives.co.uk/fullstory.asp?id=1112 (accessed May 3rd 2013).
[8] Hermansson T, Bohlin R, Carlson J S, Söderberg R.”Automatic assembly path planning for wiring harness installations”, Journal of manufacturing systems 32 (3), 417-422, 2013.
[9] Saboori, B; Saboori, B. “Development of roller hemming process in automotive industry - Saab Automobile AB”, Chalmers University of Technology, Göteborg. 2009.
[10] Kressin, J., “PATH OPTIMIZATION FOR MULTI-ROBOT STATION MINIMIZING DRESSPACK WEAR”, Master thesis, Chalmers University of Technology Department of Signals and Systems, May 2013.
[11] Carlson J S, Spensieri D, Wärmefjord K, Segeborn J, Söderberg R. ”Minimizing Dimensional Variation and Robot Traveling Time in Welding Stations”, Procedia CIRP 23, 77-82, 2014.
[12] Hermansson, T. et al. “Identification of material parameters of complex cables from scanned 3D shapes“, submited to Procedia CIRP.